Absolute Dating and the Astronomical Theory of Glaciation

Changes in climate occur in response to periodic variations in the earth's tilt and precession.

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Of the innumerable theories that have been proposed regarding the cause of the cyclic changes in Pleistocene climate, only that based on perturbations in the earth's orbit is subject to convincing experimental verification. The chronology for insolation maxima that is calculated from the known periodicities of the tilt and precession of the earth's axis and from the earth's orbital eccentricity can be compared with curves based on absolute dating of events in climate-controlled systems. Agreement of the two curves over several cycles would provide strong evidence for a cause-and-effect relationship.

Whereas the carbon-14 method of dating does not provide age data over a time interval sufficiently long for making such studies, results based on the recently developed protactinium-231/thorium-230 method for dating deep-sea sediments (back to 140,000 years) and the Th^{230} growth method for dating carbonates (back to 200,000 years) allow such comparison. Emiliani (*1*) was the first to point out the similarity between the climatic curves based on O^{18}/O^{16} ratios for fossil organisms in deep-sea cores and the curve, given by Van Woerkom (*2*), for summer insolation in the high northern latitudes. Figure 1 shows an impressive similarity between the two curves for the past 200,000 years. There are two main differences: (i) whereas the last change from cold to warm in the insolation curve (Fig. 1, top) had its midpoint 17,000 years ago, the corresponding change in oceanic climate (Fig. 1, bottom) occurred 11,000 years ago, and (ii) the insolation maximum at 48,000 years ago does not have a prominent counterpart in the oceanic record or, as discussed below, in the continental record.

The purpose of this article is to show that (i), if a different assumption is made regarding the relative importance of precession and tilt in constructing the insolation curve, the maximum at 48,000 years ago is greatly depressed without significant alteration of the other main features of the curve; (ii) the lag problem can be circumvented by assuming that the abrupt transitions between two stable modes of operation of the ocean-atmosphere system are triggered by prominent insolation maxima or minima; and (iii) not only the chronology for temperatures of the oceans but also the prominent glacial maximum at 18,000 years ago and the high stands of sea that occurred 80,000 and 120,000 years ago are natural consequences of this model.

Depression of Insolation Peak of 48,000 Years Ago

The seasonal and geographic distribution of solar radiation received by the earth varies in a complex periodic fashion. The distribution depends on variations in the tilt of the earth's axis with respect to the moving ecliptic (hence on the obliquity of the ecliptic), on precession of the earth's axis, and on variations in the eccentricity of the earth's orbit. In developing his theory, Milankovitch (*3*) assumed that glaciations correspond to periods during which the high northern latitudes receive a minimum of summertime solar radiation. Such minima occur (i) when the tilt of the earth's axis is smallest (period, ~ 41,000 years), and (ii) when the summer solstice occurs when the earth is at aphelion (period, ~ 21,000 years). Since the magnitude of the precessional effect is directly proportional to the eccentricity of the earth's orbit, cyclical variation in eccentricity (period, ~ 90,000 years) modulates the precessional cycle. The timing and relative amplitudes of the tilt and of the precessional cycles for the past 150,000 years, as given by Van Woerkom (*2*), are shown in Figs. 2 and 3. The magnitudes are expressed directly in terms of the primary astronomical parameters—that is, in terms of tilt angle (Fig. 2) and orbital eccentricity (Fig. 3).

The resultant of these two independent effects depends upon their relative importance. Milankovitch chose to weight them in accord with the insolation changes they induce at latitudes at which the continents are covered by large ice sheets. As the tilt effect is prominent at high latitudes and negligible at low latitudes, any redistribution of heat between these latitude zones would lead to a smaller tilt effect at high latitudes than that assumed by Milankovitch. The precessional effect, on the other hand, is more uniform throughout the hemisphere. Thus it is of interest to consider the consequence of reducing the assumed importance of tilt relative to precession.

A rather good approximation to the insolation curve can be simply achieved by making calculations for only those points corresponding to precessional maxima and minima and joining them with a smooth curve. It is assumed that the magnitude of a given insolation peak varies linearly with the tilt angle and with the orbital eccentricity. The magnitudes of the peaks are computed as follows:

$$f_W = \frac{E + x\Delta\theta}{E_{116} - x\Delta\theta_{116}}$$

$$f_C = \frac{E - x\Delta\theta}{E_{116} - x\Delta\theta_{116}}$$

where E is the eccentricity (in percent); $\Delta\theta$ is the deviation (in degrees) from mean tilt (23.1°); x is the weighting factor (hence the ratio of the magnitude of the precession to the tilt effect); and f_W and f_C are the ratios of the magnitudes of individual insolation maxima and minima to the magnitude of the minimum at 116,000 years ago (the largest) (Fig. 3). The

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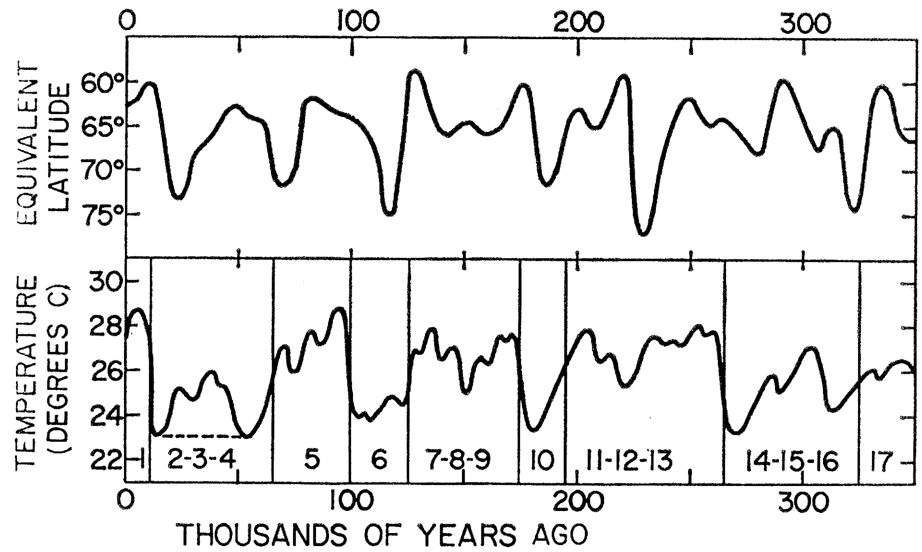

Fig. 1. Comparison of (top) the curve for summertime insolation in the Northern Hemisphere, given by Van Woerkom (*2*), and (bottom) the idealized curve for temperatures of the surface waters of the Atlantic Ocean, given by Emiliani (*1*). The dotted line is added in period 2-3-4 to indicate that most deep-sea cores do not show the warm peak Emiliani (*1*) gives in his curve (see, for example, Fig. 6).

Table 1. Calculation of relative magnitudes, *f*, of precessional insolation minima for various weighting factors, *x*.

Time of* maximum (10^3 yr ago)	E* (%)	$\Delta\Theta$* (deg)	f†		
			$x = 5$	$x = 2.5$	$x = 1.2$
0.0	1.67	0.4	0.03	−0.10	−0.22
22.1	1.69	−1.1	−0.79	−0.67	−0.57
47.5	1.26	1.2	0.52	0.26	0.04
71.2	2.44	−0.3	−0.43	−0.49	−0.52
94.1	3.42	1.1	0.23	−0.09	−0.38
116.1	4.12	−1.0	−1.00	−1.00	−1.00
138.8	2.97	0.2	−0.22	−0.38	−0.51
163.6	2.88	0.5	−0.04	−0.24	−0.42
186.9	4.52	−0.3	−0.66	−0.80	−0.91
208.8	4.77	0.7	−0.14	−0.45	−0.73
231.1	4.29	−0.8	−0.91	−0.96	−0.98
253.9	2.35	1.0	0.29	0.02	−0.20
280.2	3.05	−0.1	−0.39	−0.50	−0.59
302.2	4.40	−0.1	−0.54	−0.71	−0.85

* Data based on Van Woerkom's calculations (*2*). † Minus sign indicates deviation toward lower-than-average summertime insolation.

Table 2. Calculation of relative magnitudes, *f*, of precessional insolation maxima for various weighting factors, *x*.

Time of* maximum (10^3 yr ago)	E* (%)	$\Delta\Theta$* (deg)	f†		
			$x = 5$	$x = 2.5$	$x = 1.2$
11.2	1.92	1.1	0.82	0.71	0.62
33.2	1.21	−0.5	−0.14	0.00	0.11
60.1	1.93	−0.8	−0.23	−0.02	0.17
82.4	2.88	0.6	0.65	0.67	0.67
105.9	3.96	−1.0	−0.11	0.23	0.50
126.9	3.80	0.9	0.91	0.91	0.92
151.0	2.30	−0.4	0.03	0.20	0.33
175.7	3.89	0.4	0.65	0.74	0.82
197.7	4.75	−0.6	0.19	0.49	0.75
220.3	4.65	0.4	0.73	0.85	0.96
242.0	3.53	−0.8	−0.05	0.23	0.47
268.1	1.90	−0.3	0.05	0.17	0.29
291.0	3.99	0.7	0.82	0.87	0.91

* Data based on Van Woerkom's calculations (*2*). † Minus sign indicates deviation toward lower-than-average summertime insolation.

difference in sign for the term $\Delta\Theta$ results from the fact that the magnitude of maxima increases with increasing tilt, whereas that of minima decreases with increasing tilt. The f values all lie between +1 and −1; negative and positive values indicate, respectively, values lower and higher than mean summer insolation in the Northern Hemisphere. Not all insolation minima resulting mainly from precessional effects have negative f values and not all maxima resulting mainly from such effects have positive f values, because phase reversals allow the tilt effect to completely cancel the effect due to precession.

The results of calculations for x values of 5, 2.5, and 1.2 are given in Tables 1 and 2. The corresponding curves are shown in Fig. 4. The times of precessional maxima and minima, the orbital eccentricities, and the tilt angles used in these calculations are those given by Van Woerkom (*2*).

Comparison of the three curves of Fig. 4 indicates that, within the last 200,000 years, a reduction in the relative importance of insolation attributable to tilt has the greatest influence on the portion of the curve representing the period 30,000 to 65,000 years ago. Because an exact phase reversal (hence a tilt maximum matching a precessional minimum) occurs 48,000 years ago, a reduction in the tilt weighting greatly reduces the prominent warm peak found at this time in the Milankovitch curve. The overall effect is generation of a long period of intermediate climate between the insolation minima at 71,200 and 22,100 years ago. We have a somewhat similar situation at 250,000 years ago. An extreme reduction in the relative contribution of tilt (dotted curve) generates prominent insolation maxima at 242,000, 198,000, and 106,000 years ago and prominent minima at 209,000, 164,000, and 139,000 years ago. The solid curve ($x = 5$) approximates the usual insolation curve.

The phase reversal at 48,000 years ago is unique in that a reduction of this maximum to intermediate status does not produce any other equally significant changes in the curve. As stated above, such a reduction can be justified by the assumption that redistribution of heat between low and high latitudes partially compensates for the reduction of insolation at high latitudes caused by changes in the tilt of the earth's axis.

Astronomical Changes and the Oceanic Record

Results of radiocarbon dating provide a detailed chronology of the changes in climate which have taken place during the last 25,000 years. The oceanic record for this period shows only one prominent feature, a sharp unidirectional change, with its midpoint at 11,000 years ago, from cold to warm surface water. The most rapid retreat of the continental ice sheets, the most important vegetational changes (as recorded by pollen), and the large oscillations which marked the end of pluviation in the Great Basin also took place at this time. Hence, as pointed out by Broecker *et al.* (*4*), there is little doubt that 11,000 years ago marks the midpoint of a rapid transition from glacial to the interglacial conditions.

As the last insolation maximum occurred 11,200 years ago, it is reasonable to postulate that this maximum is responsible for the termination of the last glaciation. If this was the case, then earlier transitions from glacial to interglacial conditions may also have occurred in response to prominent insolation maxima.

In order to test this hypothesis the following model for climatic cycles is postulated. The assumption is made that the earth has two stable modes of operation of the ocean-atmosphere system, glacial and interglacial. Although oscillations about these stable configurations take place, the system is always in one mode or the other. It is assumed that rapid transitions from one mode to the other occur in response to insolation maxima for which f_W is in excess of 0.55 and to insolation minima for which f_C is in excess of -0.35. By making the further assumption that $x = 3.7$, the timing of alterations from glacial to interglacial climate is fixed. The sequence predicted for the past 300,000 years is shown in Fig. 5. Boundaries established by Emiliani (*1*) for warm and cold intervals in the oceanic record (from temperature estimates based on O^{18}/O^{16} ratios for fossil organisms in deep-sea cores and from age determinations obtained with the C^{14} and the Pa^{231}/Th^{230} techniques) are given, for comparison, in Table 3.

Within the past 180,000 years, the period for which dating techniques give reliable results, five of the six age determinations agree with the pre-

Table 3. Comparison of (*i*) data predicted from the model described in the text with (ii) Emiliani's estimates (*1*) based on O^{18}/O^{16} temperatures for fossil organisms in deep-sea cores and on absolute age data obtained with C^{14} and Pa^{231}/Th^{230} techniques.

Prediction*				Observation				
Period	Beginning (years ago)	End (years ago)	Length (*L*) (yr)	Period†	Beginning (years ago)	End (years ago)	Length (*L*) (yr)	L_{pred}/L_{obs}
W–1	11,200	—	—	1	11,000‡	—	—	(1.0)
C–1	71,200	11,200	60,000	2–4	65,000§	11,000	54,000	1.1
W–2	82,400	71,200	11,200	5	100,000§	65,000	35,000	0.3
C–2	116,100	82,400	33,800	6	125,000§	100,000	25,000	1.4
W–3	175,700	116,100	59,600	7–9	175,000‖	125,000	50,000	1.2
C–3	186,900	175,700	11,200	10	195,000‖	175,000	20,000	0.5

* $x = 3.7$; boundary limits, -0.35 and $+0.55$ heat units. † For further definition of these periods, see Fig. 1. ‡ Value established by C^{14} dating. § Value established by Pa^{231}/Th^{230} dating. ‖ Value established by extrapolation.

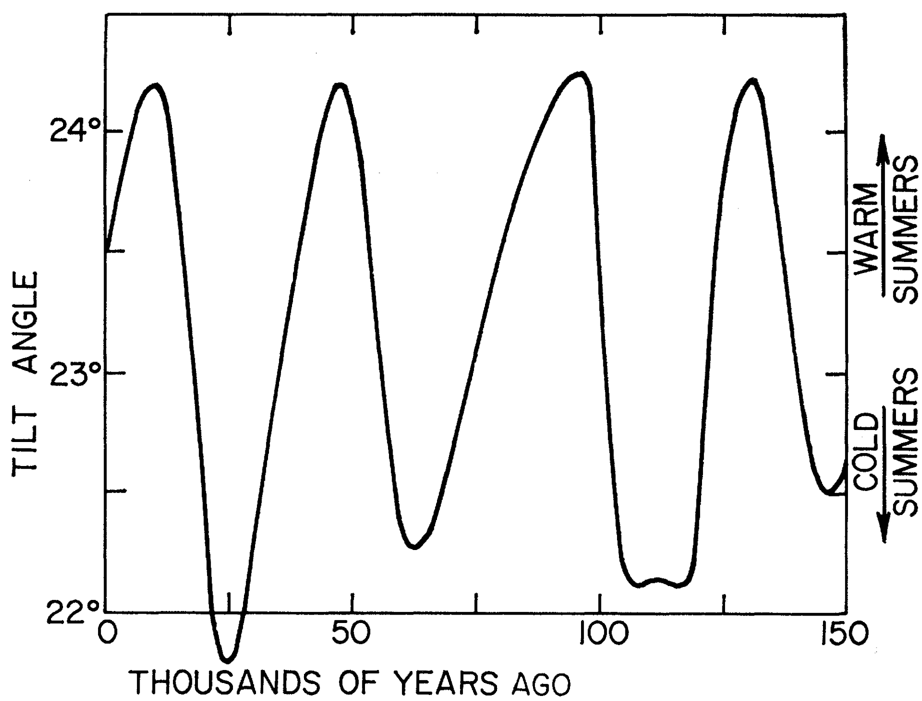

Fig. 2. Variations in the obliquity of the earth's axis (that is, in tilt with respect to the moving ecliptic) over the past 150,000 years. [After Van Woerkom (*2*)]

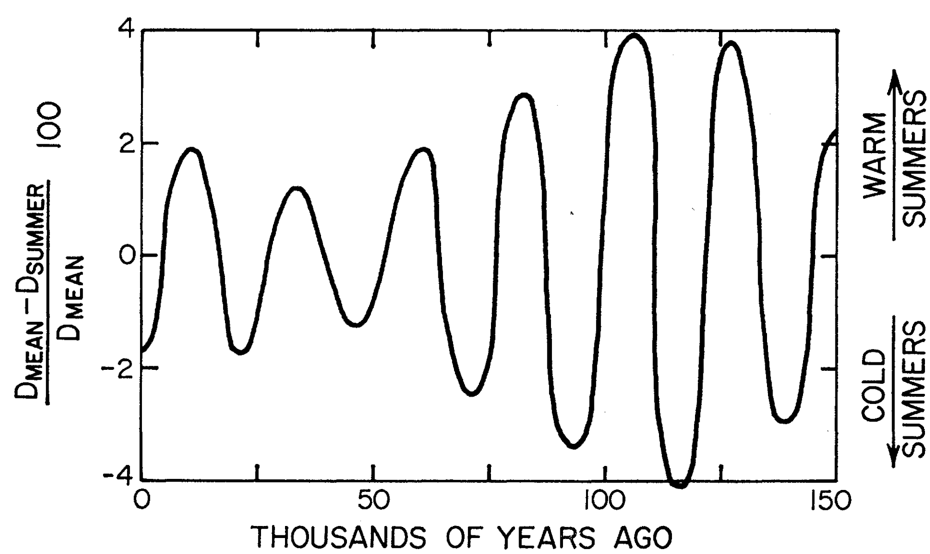

Fig. 3. The precessional cycle modulated by changes in the eccentricity of the earth's orbit over the last 150,000 years and its effect on climate in the Northern Hemisphere. (*D*) Distance of the earth from the sun. [After Van Woerkom (*2*)]

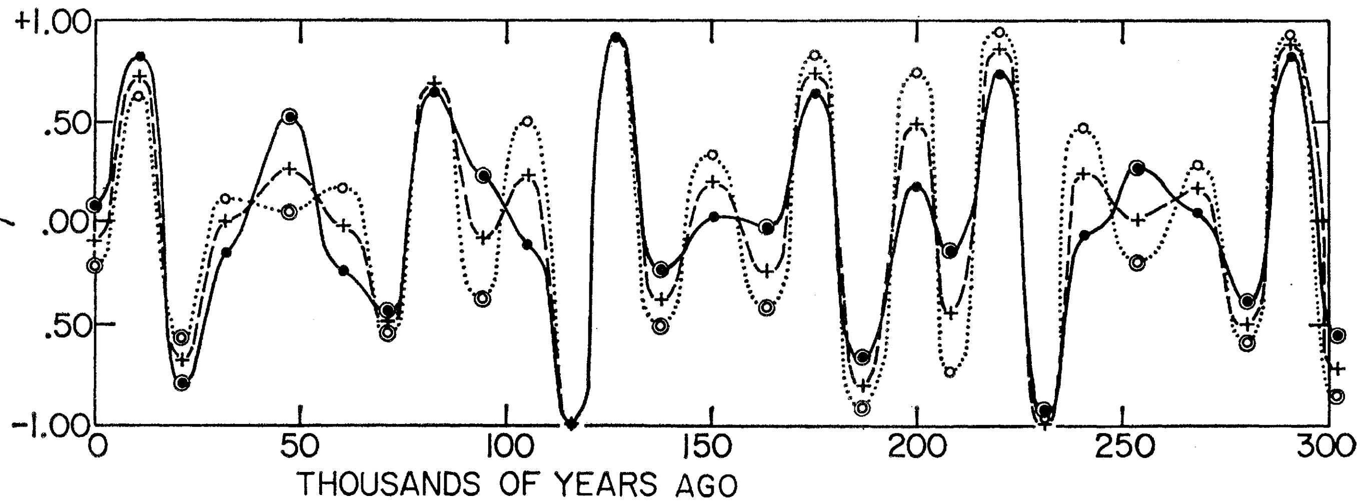

Fig. 4. Insolation curves constructed for various weighting factors (x) of tilt effect versus precession effect; (solid curve) $x = 5$; (dashed curve) $x = 2.5$; (dotted curve) $x = 1.2$.

dictions, within the uncertainties of the dating technique (±10 percent). The predicted age of 82,000 years for the boundary between W-2 and C-2 (see Table 3) is, however, 20 percent lower than the measured age of 100,000 years. This discrepancy could be explained by assuming a systematic error of 20 percent in the absolute age determinations, but the adjustment for such an error, if uniformly applied, would create a serious disagreement between prediction and observation for the next younger boundary.

Another possible way to remove the age anomaly is to lower the value of x to about 1.2. The maximum at 106,000 years ago, rather than that at 82,000 years ago, would then terminate the W-2 period. Besides removing the age anomaly this change would also entirely eliminate the insolation maximum at 48,000 years ago. It would, however, introduce an additional cycle between 220,000 and 187,000 years ago, which does not seem to be indicated in the oceanic record. There is also a question as to whether such a large reduction in the assumed tilt effect is justified.

Examination of Emiliani's (*1*) O^{18}/O^{16} curves for individual deep-sea cores shows that the cold-to-warm transitions are more prominent and sharp than the warm-to-cold transitions (see Fig. 6). Sudden warming of the climate occurred close to 175,000, 100,000, and 11,000 years ago. In each case these changes correspond to the insolation maximum immediately following a prominent minimum. Thus, if the simple model given above proves unsatisfactory, an approach based on this relationship could be pursued.

The question arises, How sensitive are the predictions to the selection of x and of the peak size necessary to trigger the system from one mode to the other? The multiplier x can be reduced until the pair of insolation maxima and minima at 200,000 years ago create the additional cycle mentioned above (this would require $x < 2.5$) and increased until the peak at 48,000 years ago creates another cycle ($x > 5.5$). The f values for insolation minimum can vary from −0.45 to −0.30 without changing the pre-

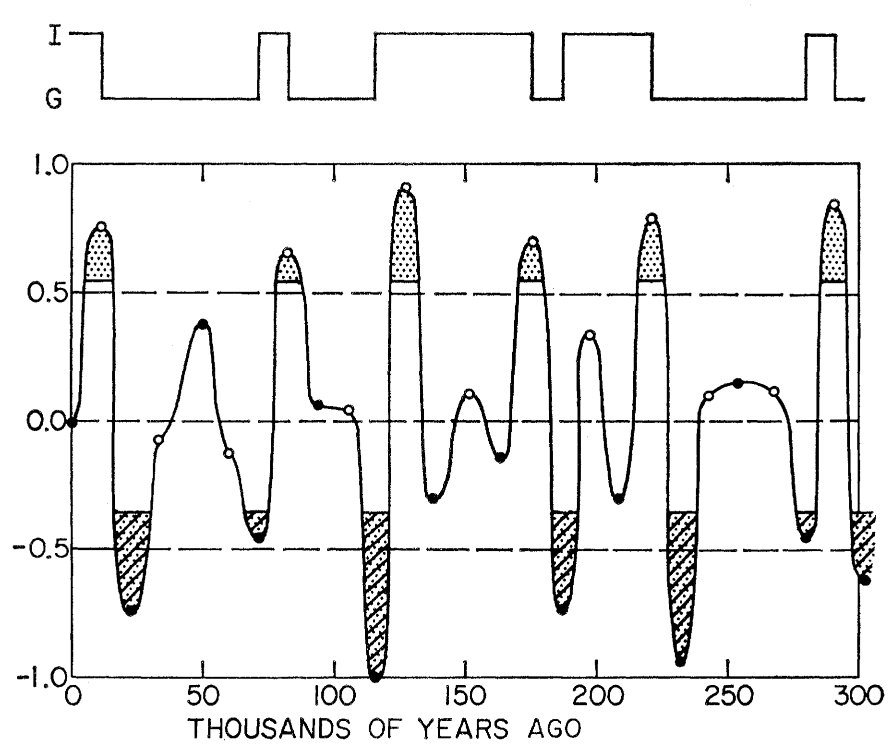

Fig. 5. (Bottom curve) Northern Hemisphere summer insolation based on $x = 3.7$. Dotted areas represent those portions of warm peaks capable of triggering the system from a glacial to interglacial mode of operation of the ocean-atmosphere system. The hatched areas are those portions of the cold peak capable of returning the system to its glacial mode. (Top curve) Predicted modes as a function of time, derived from these triggers. (*I*) Interglacial mode; (*G*) glacial.

dictions, and those for the maximum, from 0.65 to 0.40. The standard Milankovitch curve, for example, would yield the original set of predictions.

Astronomical Changes and the Continental Record

Climate curves based on ice volume as measured by sea level or by area of glacial coverage, or by both, differ from curves based on ocean-water temperatures in one very important respect. Whereas the oceanic record shows an abrupt change from warm to cold beginning after 13,000 years ago and ending before 9000 years ago, the glacial record shows a much more gradual change. The retreat of the ice from the last major ice maximum began about 18,000 years ago, and present-day conditions were not achieved until about 5000 years ago. Further, an important ice advance took place between about 25,000 and 19,000 years ago, which has no prominent counterpart in the oceanic record.

This climate curve based on sea level and extent of glacial coverage can be generated from the curve for summertime insolation in the Northern Hemisphere if it is assumed that (i) the glaciers respond both directly, as a result of changes in insolation, and indirectly, as a result of the transitions in climatic mode postulated for the ocean-atmosphere system, and that (ii) there is a lag between these changes and the glacial response. As shown in Fig. 7, if the magnitude of the insolation change induced by the mode switch is assumed comparable to the magnitude of the astronomical change, and if the half-response-time for the continental glaciers is taken to be 3000 years, then an ice-volume curve consistent with observation is obtained.

Further support for the astronomical theory is obtained if these same assumptions are used to construct a predicted ice-volume curve for the past 180,000 years (see Fig. 8). The predicted glacial minima (hence sea-level maxima) for this interval fall at 120,000 and 80,000 years ago. In order of importance, glacial maxima at 20,000, 110,000, and 60,000 years are predicted.

Recent results based on the Th^{230}/U^{234} method of dating marine carbonates clearly indicate that a prominent stand of the sea higher than the present-day sea stand occurred close to 120,000 years ago throughout the world. Thurber *et al.* (*5*) demonstrated this event at Eniwetok; Stearns and Thurber (*6*), in the Mediterranean; Broecker and Thurber (*7*), in the Florida Keys; Broecker and Kaufman (*8*), in Southern California; and Veeh (*9*), in the islands of the Pacific and Indian oceans.

Although less prominent, occurrence of a stand close to 80,000 years ago also has been documented. Stearns and Thurber (*6*) have good evidence for

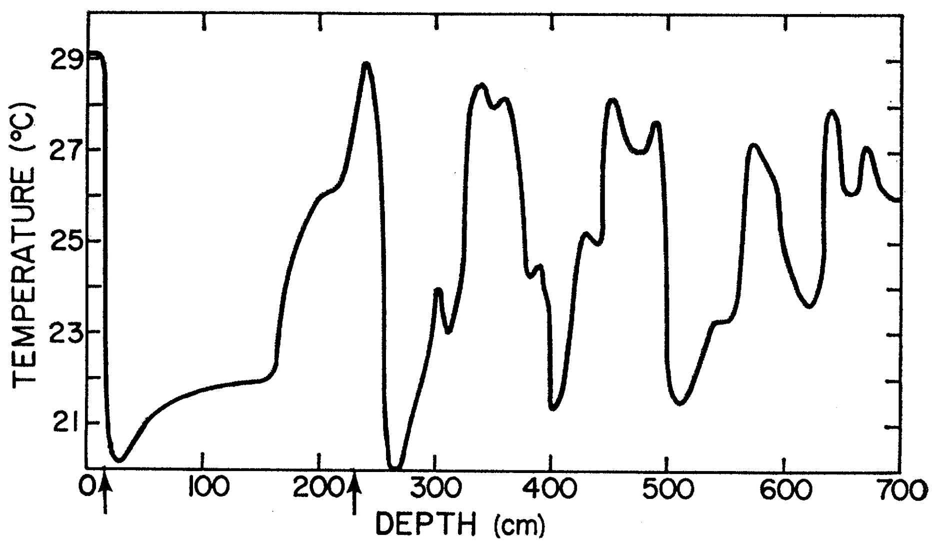

Fig. 6. Plot of temperatures derived from O^{18}/O^{16} ratios for the planktonic species *Globigerinoides sacculifera* (*1*) as a function of depth in Caribbean core A179-4 (16°36′N, 74°48′W, 2965 meters).

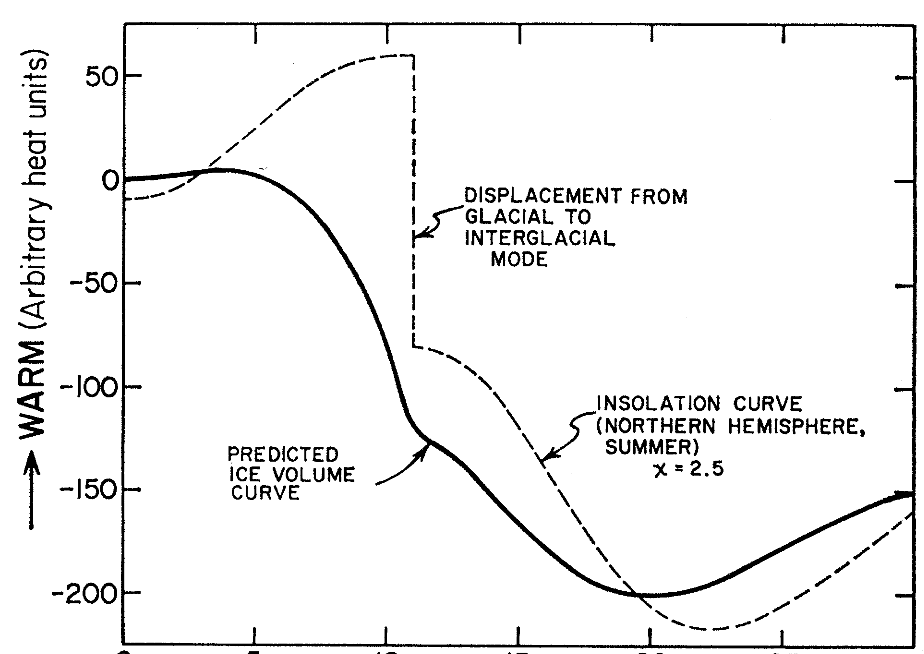

Fig. 7. Relationship between modified curve (dashed) for summertime insolation in the Northern Hemisphere and the predicted ice-volume curve (solid) generated therefrom on the basis of an assumed half-response-time of 3000 years. The predicted curve matches observation—that is, it shows an ice maximum close to 19,000 years ago followed by a glacial retreat lasting until about 5000 years ago, and little change over the last 5000 years.

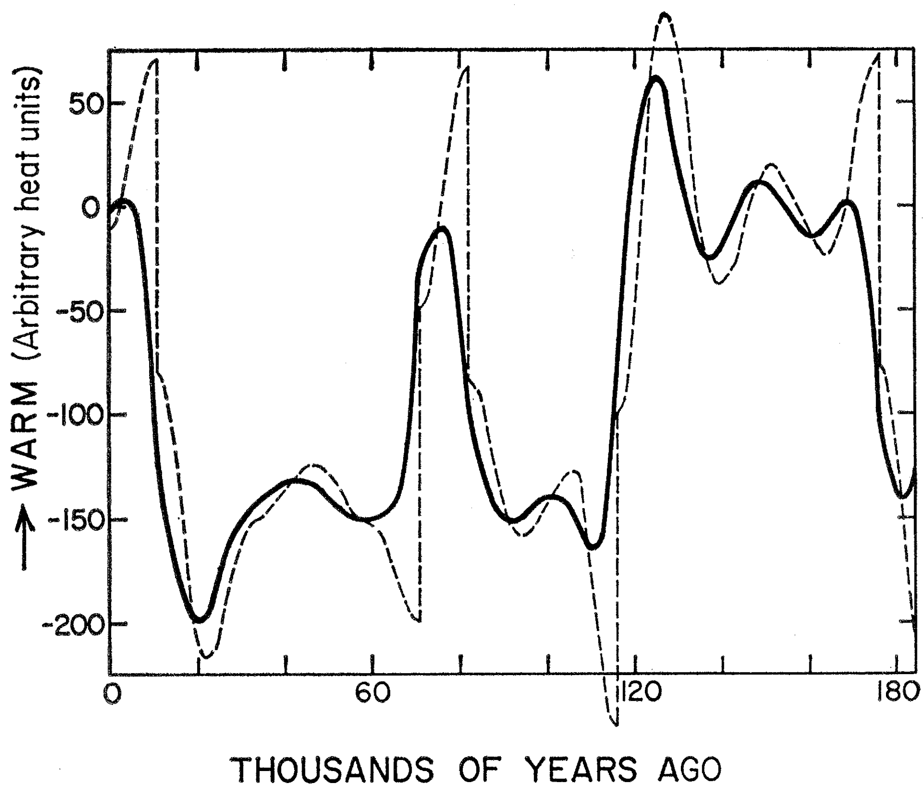

Fig. 8. Predicted curve (solid) for ice volume for the past 180,000 years, generated from the modified curve (dashed) for insolation on the basis of an assumed half-response-time of 3000 years.

the events of 80,000 and 120,000 years ago in the Mediterranean, and Broecker and Thurber (*7*) have one firm date for a raised coral in the Bahamas. No indication of high sea stands between 80,000 and 5000 years ago has been found.

When we turn to the record of glacial maxima, less definite evidence is available. Dreimanis and Vogel (*10*), on the basis of glacial evidence from the Lake Erie region, conclude that, during the period from more than 50,000 years ago to about 25,000 years ago, the ice margin stood several hundred kilometers north of its position at the time of the glacial maximum of 19,000 years ago. No firm dates for glacial advances in the period from 150,000 to 50,000 years ago have been obtained. A crucial test of this hypothesis is, thus, demonstration of the occurrence of a moderately strong glacial advance about 110,000 years ago.

Summary. A simple hypothesis explaining the major features of the accepted chronology for climate over the past 200,000 years has been constructed. Although based on changes in insolation, it differs from the Milankovitch approach in the following important respects. The concept of fluctuations about a mean climate in response to changes in insolation is modified by assuming that the ocean-atmosphere system has two stable states or modes, glacial and interglacial; that rapid transitions between these states are triggered by the larger insolation peaks; and that fluctuations about these states occur in response to insolation changes not large enough to cause mode transitions. This hypothesis not only provides a reasonable explanation for the timing of the observed fluctuations in oceanic climate but also explains the prominent ice maximum that occurred 19,000 years ago and the high stands of the sea that occurred 80,000 and 120,000 years ago.

References and Notes

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